Off-Axis Ratcheting Behavior of Unidirectional Carbon/Epoxy Laminate under Asymmetric Cyclic Loading at High Temperature

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Abstract

Development of an engineering model for predicting the off-axis ratcheting behavior of a unidirectional CFRP laminate has been attempted. For this purpose, the ratcheting behavior of a unidirectional carbon/epoxy laminate under off-axis cyclic loading at high temperature is studied with emphasis on its dependence on load waveform (i.e. stress ratio) and fiber orientation. First, off-axis ratcheting tests with different levels of maximum and non-zero mean stresses are performed on coupon specimens with different fiber orientations, respectively. The experimental results show that the accumulation of ratcheting strain occurs in the unidirectional CFRP laminate, regardless of fiber orientation, and the off-axis ratcheting behavior is similar to the off-axis transient creep behavior in all aspects of its stress, time and fiber orientation dependence. It is shown that the proposed model allows adequately predicting the off-axis ratcheting behavior of the unidirectional CFRP laminate for different stress ratios as well as for different fiber orientations.

1. Introduction

Structural components made of carbon fiber reinforced plastics (CFRPs) are usually subjected to not only static load but also cyclic load with a certain periodicity that depends on applications. It is well known that engineering materials, such as metals and polymers, exhibit creep deformation that develops with time in the loading direction under constant external load (or stress). Similar strain accumulation occurs in the direction of mean stress under asymmetric cyclic loading even if it is not accompanied by a hold period during cyclic loading. The progressive accumulation of strain with continuously varying load in the latter case is called ratcheting (or cyclic creep). For the reliable design of the machines and structures that needs the setting of allowable dimensions, therefore, it is crucial to accurately evaluate the accumulation of ratcheting strain under asymmetric cyclic loading as well as the accumulation of creep strain under constant static load. As far as the present authors know, however, the ratcheting behavior of unidirectional CFRP laminates has not fully been studied yet, and thus the influence of fiber orientation and cyclic waveform has not quantitatively been understood. For this reason, the problem of formulating an engineering constitutive model for describing the ratcheting behavior of unidirectional CFRPs under asymmetric cyclic loading has not fully been discussed so far. Therefore, quantification of the ratcheting behavior of CFRPs by experiment and development of an engineering method for predicting it are demanded for technological advance in design analysis of CFRP structures.

The present study aims to elucidate the off-axis ratcheting behavior of a unidirectional CFRP laminate at high temperature and to develop an engineering constitutive model for predicting it. Off-axis ratcheting tests are carried out on a unidirectional carbon/epoxy laminate under cyclic loading in a triangular waveform at high temperature. The ratcheting tests are performed for different fiber orientations, stress ratios, and maximum stress levels to observe the effects of for different fiber orientation and wave form of cyclic loading on the

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14. ABSTRACT
Development of an engineering model for predicting the off-axis ratcheting behavior of a unidirectional CFRP laminate has been attempted. For this purpose, the ratcheting behavior of a unidirectional carbon/epoxy laminate under off-axis cyclic loading at high temperature is studied with emphasis on its dependence on load waveform (i.e. stress ratio) and fiber orientation. First, off-axis ratcheting tests with different levels of maximum and non-zero mean stresses are performed on coupon specimens with different fiber orientations, respectively. The experimental results show that the accumulation of ratcheting strain occurs in the unidirectional CFRP laminate, regardless of fiber orientation, and the off-axis ratcheting behavior is similar to the off-axis transient creep behavior in all aspects of its stress, time and fiber orientation dependence. It is shown that the proposed model allows adequately predicting the off-axis ratcheting behavior of the unidirectional CFRP laminate for different stress ratios as well as for different fiber orientations.

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ratcheting in the unidirectional CFRP laminate. The off-axis ratcheting behavior is compared with the off-axis creep behavior of constant loading to examine the similarity and difference in between. Then, an engineering method for describing the off-axis ratcheting in the unidirectional CFRP laminate is developed. The proposed off-axis ratchet model is formulated to account for the effect of maximum cyclic stress as well as that of the mean stress, and it can predict the off-axis ratcheting deformation on the basis of the off-axis creep deformation. Finally, the applicability of the proposed off-axis ratchet model is evaluated by comparing with experimental results.

2. Experiment

2.1 Material and Specimen

The material used in this study is a unidirectional composite T700S/2592. The 12-ply unidirectional carbon/epoxy laminates $[0]_{12}$ were fabricated from the prepreg tape of P3252-20 (TORAY). They were laid up by hand and cured in autoclave. The standard coupon specimens based on the testing standards JIS K7076 [1] were employed. Straight-sided test specimens with different fiber orientations θ = 30, 45, and 90° were cut from the 400 mm by 400 mm unidirectional laminate panels, respectively, to dimensions of 100 mm long by 10 mm wide. Rectangular-shaped aluminum alloy tabs of 45 mm long were glued on both ends of the specimens with epoxy adhesive to protect their gripped portions.

2.2 Testing Procedures

Off-axis ratcheting tests were carried out at 70°C. Cyclic load was applied to specimens in a triangular waveform at a constant nominal stress rate of 100 MPa/min. Two kinds of triangular waveforms with different stress rations $R = \sigma_{min}/\sigma_{max} = 0$ and –0.3 were considered in the ratcheting tests for each fiber orientation. The maximum stress levels of the cycle loading tests were chosen to be larger than the proportional limit of the stress-strain curve for each fiber orientation; typically, they are 45% (0.45UTS), 55% (0.55UTS) and 60% (0.6UTS) of the ultimate tensile strength (UTS) for each fiber orientation. Off-axis creep tests were also performed at constant stress that is equal to the maximum levels of cyclic load for the ratcheting tests. The off-axis cyclic loading tests were conducted on a closed-loop hydraulic MTS-810 testing machine.

3. Experimental Results and Discussion

3.1 Off-Axis Hysteretic Response

Typical stress-strain curve (hysteretic response) for the fiber orientation θ = 30° that corresponds to the cyclic loading at R = 0 is shown in Fig.1. It can clearly be observed that the strain accumulates in the tensile direction with cyclic loading. The stress-strain curves for cyclic loading and unloading turn more difficult to be distinguished with increasing number of cycles, suggesting that the increment of ratcheting strain per cycle decreases with increasing number of loading cycles.

Fig.2 shows the stress-strain curves for the selected cycles N = 1, 50, 100 and 400 during the ratcheting test at R = 0. In this figure, we can clearly observe a hysteretic response to each cycle of loading and unloading over the whole range of ratcheting test. It is obvious from this figure that the center of stress-strain hysteretic moves in the tensile direction with cyclic loading. This proves that uniaxial ratcheting has certainly occurred in the unidirectional composite subjected to asymmetric cyclic loading. Incidentally, no significant change can be seen in the shape of hysteretic curve, even if the number of cycles increases. Furthermore, the average strain of the stress-strain curve for a given cycle of tension-compression loading at

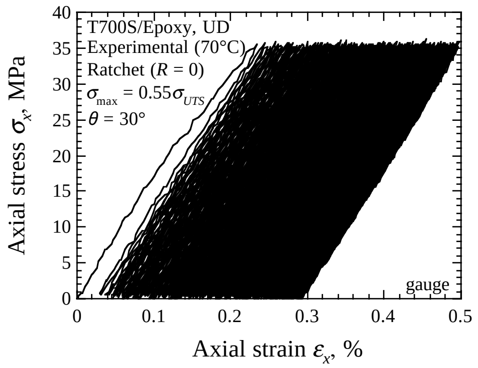


Fig.1 Off-axis ratcheting behavior (θ = 30°)

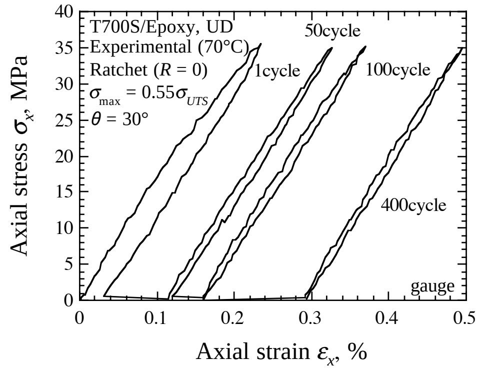
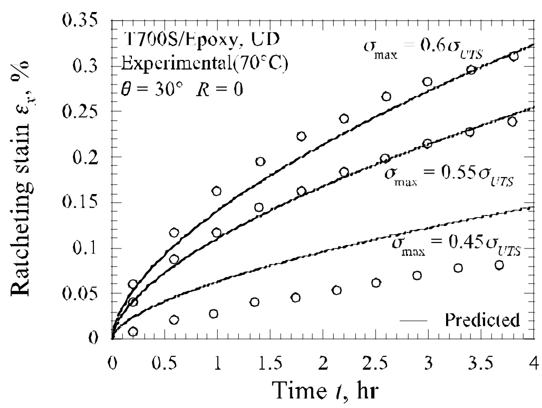


Fig.2 Off-axis hysteretic behavior (θ = 30°)

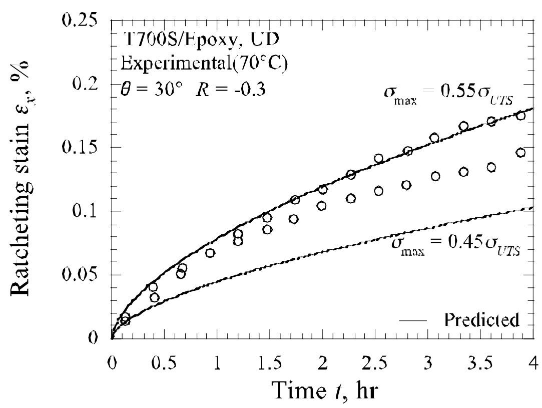
R = –0.3 increased in the tensile direction with increasing number of cycles, in line with the above-mentioned results for R = 0. The ratcheting behavior for the other fiber orientations θ = 45 and 90° was similar to that for θ = 30°, although the amount of ratcheting strain depends on the fiber orientation.

3.2 Off-Axis Ratcheting Curve

Fig. 3(a) shows the off-axis ratcheting curves for the fiber orientation θ = 30° that were obtained by the cyclic loading tests with different maximum stress levels but the same stress ratio R = 0. The symbols in this figure indicated the ratcheting test results for different values of maximum cyclic stress $\sigma_{\max}$ = 0.45UTS, 0.55UTS, and 0.6UTS, respectively. From this figure, we can see that the off-axis ratcheting strain increase as the maximum cyclic stress increases. It is also seen that the ratcheting strain rate (%/h) decreases with time, equivalently as the number of cycles increases, regardless of the maximum stress level. It is suggested by Fig.3(a) that the off-axis ratcheting behavior for θ = 30° involves not only a transient stage (i.e., ratcheting hardening) in which the ratcheting strain increment per cycle decrease with increasing number of cycles, but also approximately a steady stage in which the ratcheting strain accumulates at a constant rate.



(a) R = 0



(b) R = –0.3

Fig.3 Off-axis ratcheting curves for asymmetric cyclic loading (θ = 30°)

Fig. 3(b) shows the off-axis ratcheting curves for the same fiber orientation $\theta = 30°$ but for a different stress ratio R = –0.3. It is seen that transient and near steady-state ratcheting responses are involved by the test results for R = –0.3. The ratcheting curves for other fiber orientations also showed the transient as well as the near steady-state stages that are similar to those for θ = 30°. The transient and near steady-state stages involved by ratcheting deformation of the unidirectional CFRP laminate are similar to those involved by the creep deformation that develops under constant load.

4. Modeling of Off-Axis Transient Ratcheting Behavior

4.1 Modeling

An engineering method for describing the transient off-axis ratcheting behavior of unidirectional composites was developed. It is based on the Bailey-Norton rule for transversely isotropic materials and a modified effective stress that considers the effects of cyclic maximum stress as well as cyclic mean stress (i.e., stress ratio). The engineering constitutive model developed in this study for the unidirectional CFRP laminate subjected to asymmetric cyclic loading is expressed as

$$\frac{\varepsilon_{11}^{r} / \sqrt{F}}{\left(\sigma_{\max}\sqrt{F}\right)^{n}} = K_C \left[\frac{1}{2}\left(1+R\right)\right]^{(1-k)n} t^{b} \tag{1}$$

where ε_{11}^{r} is ratcheting strain and $\sigma_{\max}$ is the maximum stress level of cyclic loading, and t is time, and R is stress ratio, and K_C, n, k and b are the material constants. The creep (or ratchet) deformation that develops along the fiber direction in unidirectional CFRP laminates is usually very small. Thus, we neglect it in this study. Accordingly, unidirectional CFRP laminates are identified with transversely isotropic materials with no creeping in the fiber direction. This assumption allows expressing the orientation function F in Eq. (1) as

$$F = \mu \sin^4\theta + \nu \cos^2\theta \sin^2\theta \tag{2}$$

where μ and ν are the material constants that characterize the transverse isotropy of a given material. These material constants can be identified with fitting a straight line to the log-log plot of minimum creep rate and stress. The stress exponent n is identified with the slopes of the same plots.

In a particular case of the creep loading at R = 1, Eq. (1) may be reduced to the following form:

$$\frac{\varepsilon_{11}^{r} / \sqrt{F}}{\left(\sigma_{\max}\sqrt{F}\right)^{n}} = K_C t^{b} \tag{3}$$

This formula reveals that the coefficient K_c and the time-hardening exponent b can be determined by means of a straight line fit to the log-log plots of the values of the left- and right-hand sides of this equation. The remaining coefficient k is evaluated by fitting Eq. (4) to the data points: i.e. K_R ($R = R_{\text{selected}}$), K_R (R = 1) = K_C, and K_R (R = –1) = 0.

$$K_R = K_C \left[\frac{1}{2}\left(1+R\right)\right]^{(1-k)n} \tag{4}$$

4.2 Comparison with Experimental Results

The predictions of the off-axis ratcheting curves (R = 0 and –0.3) for the same fiber orientation θ = 30° but different values of maximum cyclic stress are shown by solid lines

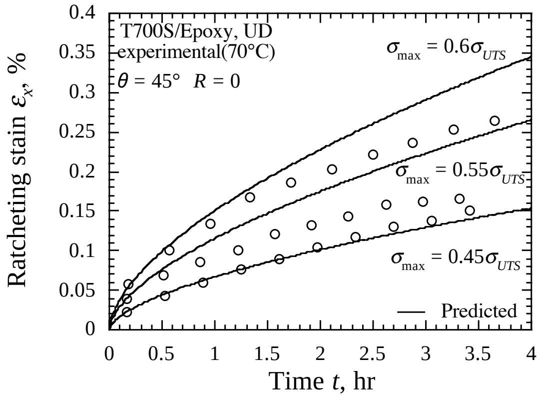


Fig.4 Off-axis ratcheting curves (θ = 45°, R = 0)

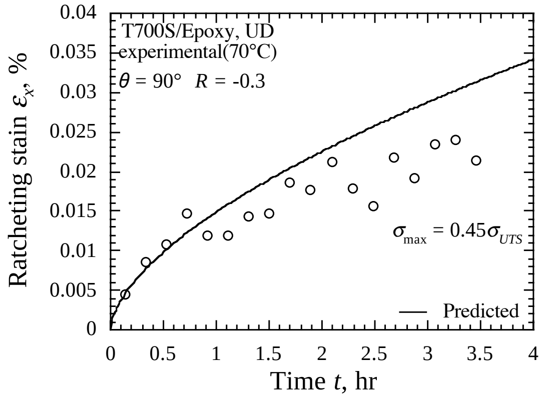


Fig.5 Off-axis ratcheting curves (θ = 90°, R = –0.3)

in Figs. 3 (a) and (b), respectively, along with the experimental results. The predictions are mostly in good agreements with the experimental results, regardless of the maximum cyclic stress and stress ratio.

Figs 4 and 5 show the predictions of the off-axis ratcheting curves for different loading conditions: θ = 45° for R = 0; and θ = 90° for R = –0.3. From these figures, it can be seen that the predictions using the transient ratcheting model are in good agreement with the experimental results, regardless of the fiber orientation, maximum cyclic stress and stress ratio.

5. Conclusions

The off-axis ratcheting behavior of a unidirectional CFRP laminate at high temperature was examined with emphasis on its fiber-orientation and stress-ratio dependence as well as its stress and time dependence. Furthermore, an engineering constitutive model for describing the off-axis ratcheting behavior of the unidirectional CFRP laminate was developed. The accuracy of prediction using the proposed model was evaluated by comparing with experimental results.

There is a general trend that a large scatter of data is normally involved by creep test results and it often becomes as large as 20% or more in a worse case, suggesting that the discrepancies between the predictions and experimental results lie within the range of scatter and thus favorable predictions have been obtained. Therefore, we may conclude that the engineering constitutive model developed in this study on the basis of the Bailey-Norton law for transversely isotropic materials allows adequately predicting the off-axis ratcheting behavior as well as the off-axis creep behavior of the unidirectional CFRP laminate over a range of stress ratio, regardless of the maximum cyclic stress and fiber orientation.

6. References

1. JIS K7076.Testing Method for Tensile Properties of Carbon Fiber-Reinforced Plastics, Japanese Industrial Standard. Japanese Standard Association, 1988.
2. H. Kraus, Creep Analysis, John Wiley & Sons, Inc., New York, 1980.